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THE PLANETESIMAL HYPOTHESIS IN RELATION TO THE EARTH

By Professor REGINALD A. DALY

HARVARD UNIVERSITY

INTRODUCTION

CHAMBERLIN'S recent book on "The Origin of the Earth" was welcomed by geologists as the most complete statement yet made for the planetesimal hypothesis of the origin of the planets.[1] Barrell has given a convenient summary of the hypothesis, in the following words:

> The volume of a star [the sun] represents a balance between expansional and condensational forces acting on a vast body of gaseous nature. On the approach [of another star] their mutual gravitation would produce tidal forces diminishing their self gravitative power along the line between the centers and give the expansive forces opportunity to rise to explosive violence along that line. This tidal force is actually greatest at the centers and would lead to a very deep-seated disruption. The gas bolts shot out would, owing to viscous resistances, be pulsatory, and separated nuclei would therefore be expelled. These nuclei and the associated dispersed matter would, on the nearer side, be dragged sideways by the passing star. On the reverse side the symmetrical tidal protrusions would be left behind, the sun being dragged more than they. The result would be a spiral nebula, a form which would meet the dynamic demands of the existing solar system. . . .
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> The building up of the planets is believed to have followed three stages: first, the direct condensation of the nuclear knots of the spiral into liquid or solid cores; second, the less direct collection of the outer, or orbital and satellitesimal matter; third, the still slower gathering up of the planetesimal material scattered over the zone between adjacent planets. This third factor in Chamberlin's view is regarded as very important and he believes this diffused matter contributed much of the earth substance, very slowly and in a dust-like form. This is one of the critical points in the details of the theory, unessential to the larger framework, but upon which turns much of the development of the following argument. In earth-growth the denser planetesimal dust, Chamberlin argues, tended to be somewhat segregated into the primitive ocean basins and served to maintain in them, as the earth was built outward, a greater density than in the elevated zones between. . . .
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> The earth is conceived as beginning to hold an ocean by the time it contained 30 or 40 per cent. of its present mass. . . .
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> The particles of radioactive matter [in the earth] would tend toward

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[1] T. C. Chamberlin, "The Origin of the Earth," University of Chicago Press, Chicago, 1916.

local heating and fusion. Thus they would be progressively concentrated into the outer shell of the earth by the rising of igneous matter. Pulsatory stresses from body tides and from shrinkage are regarded as the chief agents leading fused matter outward and serving to maintain the earth's body in solid form.[2]

On the astronomic side this conception of the solar system represents one of the grandest achievements of modern science. The distribution of masses and momenta, the directions of revolution and rotation, and the constitution of each member of the system, so far as ascertained, are explained with such a degree of probability that astronomers are becoming more and more impressed by the planetesimal hypothesis. However much increasing knowledge may change premises and conclusions, the critical and creative work of Chamberlin, Moulton, and their associates has resulted in stimulus to many minds and marks a permanent advance toward a final understanding of the earth's beginning.

Chamberlin was led to his great idea while studying ancient climates, and it is natural that he has attempted to apply his cosmogony to that later part of terrestrial history which is covered by geology proper. He has recognized the exceeding difficulty of this extension of the hypothesis beyond the astronomic limits, but has courageously attacked the problem as it affects the general distribution and shapes of the existing continents and ocean basins; hence the making of assumptions which have no vital connection with the splendid cosmogony itself. Some of the subsidiary assumptions are doubtful, if not quite inadmissible, and it now looks as if general recognition of Chamberlin's working hypothesis would have been hastened if it had been announced without direct reference to the later, geological, history of our globe.

One doubtful postulate is that the earth has been essentially solid since the time when it had less than half its present mass. To a discussion of this point the present paper is devoted; the postulate is hard to reconcile with the main planetesimal hypothesis itself, on the one hand, and with leading facts of astronomy and geology, on the other.

SOME IMPLICATIONS OF THE PLANETESIMAL HYPOTHESIS

Neither the mass, nor the temperature, nor the dynamics of the original earth-knot or nucleus are deducible from the root premise of expulsion from the sun. According to some astronomers, the visible spiral nebulæ are not homologies of the planetesimal nebula. In any case one can not infer from the spirals, even in rough measure, the state of the earth nucleus immediately after its expulsion. The general hypothesis gives no direct information concerning the ratio of the mass of the knot to the mass of the existing earth. Around the earth is now a "sphere" (spheroid) of control within which our planet's gravitative influence surpasses that of the sun. The sphere of control is roughly 5,000,000 times the volume of the earth. Within so great a space nearly all of the earth's matter might have been aggregated at the nuclear stage, in spite of the high temperature prevailing at the initiation of the earth-knot. If so, condensation of the earth-knot by its own powerful gravitation would be rapid, with the consequent speedy increase of temperature. Initially hot enough to be completely gaseous, the nucleus radiated much heat, but this effect on temperature was at least partly offset by the development of heat through self-compression and chemical changes. A very large part of the initial heat and of the original potential energy would have to be lost by radiation before a liquid state were assumed and still more before a solid crust could be developed. According to Lane's law, radiation and consequent contraction would actually raise the temperature of the knot if its gas behaved like a "perfect" gas. The potential energy of such a system is far from being measured by the amount of the contraction. Doubtless a much greater part of the potential energy would manifest itself in the form of heat given off during chemical reactions in the nucleus, which was initially composed of highly dissociated elements.

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[2] J. Barrell, *Science*, Vol. 44, 1916, p. 241.

In short, the original earth-knot was, by hypothesis, a true furnace. Its generation of heat must have long continued, even if the initial mass were only one quarter of the globe's present mass. The vital question arises as to whether the gaseous knot would be solidified by cooling before most of its accretion was accomplished. *Rates* of heating, *rates* of cooling, and *rates* of accretion, as well as the initial mass and temperature of the knot are involved, and the general hypothesis bears no implication concerning any of these quantities.

Chamberlin appreciates this fact and concludes that "the temperature of the innermost core of the earth" must remain "an open question." He also states that "the mass of the planetary nucleus may have been so large and the ingathering of the planetesimals may have been so rapid, by hypothesis, that a molten or even a gaseous condition could have arisen. In the case of the larger planets such a primitive state is quite within the limits of the probabilities. The case of the earth is debatable."[3]

ASSUMPTION OF THE EARTH'S EARLY SOLIDITY

Yet, notwithstanding his own unescapable conclusion, Chamberlin believes that the earth, with a mass only about one third of its present value, was already well crusted, if not essentially crystalline to the core. He assumes that a water ocean could then lie on the earth's surface, and that the heat of self-compression, chemical heat, and heat generated in radioactivity have never sufficed, since this embryonic stage, to melt the surface shell of the globe. With these assumptions, which are not implicit in his main, astronomic hypothesis, Chamberlin proceeds to picture the juvenile shaping of the earth, in the longest chapter of his latest book. Further difficulties appear as the speculation is developed, leading to other unproved assumptions. The latter are not of immediate concern, since they rest on the conception of early, and thenceforth permanent, solidity for the earth, which is the thesis specially questioned in the present note.

TESTIMONY OF THE OTHER PLANETS

The general hypothesis assumes similar origins for all the planets. Jupiter, Saturn, Uranus, and Neptune have densities either a little less than that of water or a little greater, contrasting with the mean density of the earth, 5.5. There are apparently only two possible explanations of the contrast. The outer planets must be greatly expanded by heat, or else they must be composed of hydrogen or other elements of low atomic weights.

Each planet represents a major belch from the sun and yet also a minute fraction of the sun's substance. Now studies of the sun's photosphere, "reversing layer," and "spots" show that its surface shell, down to a depth of many hundreds of miles, is composed of both heavy and light elements. Heavy elements are likely to be still more abundant in deeper shells. We can not assume that the sun, because of higher temperature, was a "hydrogen" star when the planetary belches took place, and that the gas-bolts were shot out from the outer layer of hydrogen. This possibility is at once excluded by the facts known about the constitution of the four inner planets, the asteroids, and the satellites of the planets. Thorough mixture of heavy and light elements in the sun at the present time is plainly due to convection and explosion.[4] Both actions would doubtless have been still more intense when the sun was hotter. If, as Chamberlin thinks, the belching were due largely to explosions originating in great depth, heavy elements could hardly fail to enter into the composition of all the major belches. The greatest belches should have tapped deeper layers than those tapped by the weaker earth-belch, giving a larger percentage of heavy elements to the four outer planets.

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[3] T. C. Chamberlin, "The Origin of the Earth," Chicago, 1916, p. 164, and "The Tidal and Other Problems" (Carnegie Institution Publications, Washington, 1909, p. 18).

On this point Chamberlin writes: "The distal portions of the protuberances would be obviously formed from the superficial portions of the sun, while the later portions of the ejections forming the proximal parts of the arms would doubtless come mainly from lower depths, and hence probably contain more molecules of high specific gravity."[5] But is that conclusion justifiable? If all of the planetary material were put back in the sun, the sun's diameter would be little changed; its mass would be increased by less than one seventh of one per cent. If a mass equal to either Neptune or Uranus were removed from the sun's surface shell, the depth of the layer known to be now affected by powerful convection would be decreased by only a small fraction. The supposition that, at the birth of the planets, convection did not affect the sun's layer which was disrupted, is not easy to reconcile with the sun's present condition. To suppose that deeper layers were not tapped is to exclude the strong influence of explosion, a basal postulate of the general hypothesis. Moreover, the smaller the mass ejected, the more superficial would be the solar shell involved. All these considerations make it difficult to believe that there would be any drastic or systematic variation in the material ejected successively from the sun. One might even raise the question whether the general hypothesis demands that the earth-belch really followed in time the Jupiter or Uranus belch. If, on the contrary, the earth-belch were the older, it should, according to Chamberlin's principle above-quoted, have density lower than either of the other two; lower, too, because the earth-belch was the weakest of the three. Finally, the densities of at least two of Jupiter's satellites are too high to be explained by the hypothesis that their parent belch was made of pure hydrogen or of hydrogen mixed with helium.

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[4] The experiments of H. Bénard (*Rev. gén. Sciences*, Vol. 11, 1900, p. 1261) suggest that the granulation of the sun's surface may be due to the development of a cellular structure which is expected in any fluid layer uniformly affected by convection.

[5] T. C. Chamberlin and R. D. Salisbury, "Geology," Chicago, Vol. 2, 1906, p. 58.

Much more probably every major belch from the sun was made up of elements now engaged in the solar tornadoes—calcium, iron, barium, sodium, magnesium, silicon, etc., as well as hydrogen and helium. In fact, from a passage quoted above, Chamberlin seems to have abandoned his early view, now favoring the conclusion just stated. Perhaps yet more surely than the Laplacian hypothesis, the planetesimal hypothesis demands that all planets shall have a large proportion of elements with high atomic weights. If so, the outer planets must have very high temperatures, as so long held by astronomers.[6]

We have, then, half of the planets still so hot as to be gaseous, although, by hypothesis, they are nearly as old as the earth and are probably composed of material which is much like the average material of the earth.[7] At this late day the four outer planets must be losing heat many times faster than the earth is losing heat through a solid crust and still they are incomparably hotter than our globe. According to the planetesimal hypothesis, they are so hot because of their size. If the common mechanism produced in four full-grown planets temperatures sufficient for nearly complete volatilization of highly refractory substances, temperatures persisting after more than one hundred million years, is it reasonable to assume that the mechanism failed to produce the much lower temperature needed for surface liquefaction of a fifth planet a hundred million years ago? Do not these homologies suggest yet more—a gaseous condition for the earth after it had attained its present mass?

In summary, the planetesimal hypothesis leaves indeterminate most of the essential factors affecting the earth's successive temperatures, namely, the ratio of nuclear mass to planetary mass, the initial temperature of the earth-knot, the rate of accretion, the heating factors, the cooling factors, and the absolute time involved. Hence the present condition of the other planets ought to have special attention by any one who attempts to trace the earth's history down into "Archean" time. Perhaps we can hope for no better evidence in nature on the subject of the early temperatures of our globe.

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[6] Of course density can not give accurate intimation of temperature. Saturn, for example, with a little over half the density of Jupiter (0.7 against 1.3, water being 1.0), is not necessarily the hotter. Moderate differences in chemical constitution, together with differences in internal pressure, must also enter into the causes for the contrast.

The reasoning is not affected by the possibility of a solid core for each of the outer planets. The core must be relatively minute, for otherwise the average density would be too high to match the facts. With correspondingly great depth for the planetary atmosphere, involving pressures of tens of thousands of earth atmospheres, the average density of the planet could be low only in case the main, gaseous part of its body had high temperature.

[7] The approximate identity of age is implied by the basal postulate of disruption, for a visiting star would vitally affect the sun for only a few years, at most.

AN EARLY CRUST A BLANKET ON THE EARTH FURNACE

If, however, radiation did actually overtake heating in the young earth, with the development of a solid crust, the general hypothesis implies the likelihood that this crust would be but temporary. So far as densities are concerned, it might have been stable if the earth had already, because of fluidity, become stratified by density. On the other hand, the crust, an efficient blanket, must have brought radiation to a very low minimum. Later, considerable accretion of the earth nucleus could not fail to develop new heat by self-compression and chemical rearrangements under the new, ever-changing conditions of internal pressure. The changing conditions would affect material at all depths. The heat waves so generated would pass outward with great slowness, for convection was largely in abeyance if the earth were layered according to intrinsic density of its materials. A relatively moderate heat-wave of the kind, moving outward for but a brief time, would suffice to re-melt the crust. Each time that the surface shell became fluid, gravitative differentiation would be more perfected near the surface, with resulting retardation of convection. On one of the reasonable assumptions regarding the young earth, therefore, the planetesimal hypothesis seems to demand a cyclical or rhythmical change of state for the earth's surface shell, analogous to that observed in the lava lake at Kilauea or in other typical volcanic vents.

Be it observed, nevertheless, that the general hypothesis, as announced, does not necessitate belief in crustification (or in solidification at any depth) of the earth until it had attained its present mass.

TESTIMONY OF THE MOON

The volcanic nature of the lunar pits and maria is generally credited and seems to be implied by the planetesimal hypothesis. If the pits and the vast areas of the maria were due to the impact of bolides, these bodies would, by hypothesis, be planetesimals. They would have been practically the last to fall into the lunar nucleus, for the visible depressions are not appreciably veneered with planetesimal particles of smaller dimensions. Similar masses would have fallen into the earth during the last stage of its growth. Yet nowhere on continent or in ocean basin is comparable topography to be found. The progress of erosion can hardly account for the disappearance of every trace of such gigantic features. Moreover, the symmetry of each lunar pit does not agree with the impact hypothesis, if the great bolides were planetesimals, added to the moon's mass in the normal way.

If, by fair interpretation, the planetesimal hypothesis implies a volcanic origin for the lunar depressions, the main hypothesis also implies that, after reaching full size, one of the smaller aggregations in the solar system had internal heat enough to permit eruptivity on a scale vastly superior to the scale of volcanism on the present earth. In more or less close succession all parts of the moon's surface seem to have been affected by igneous eruption. The colossal lava-floodings of the maria have been accompanied by subsidence of the pit-covered crust in the corresponding areas, suggesting (as in the earth's similar cases) that the flooding lavas were drawn from a non-crystalline substratum close to the moon's surface.

According to the planetesimal hypothesis, the moon's volcanic heat was generated largely by self-compression and chemical rearrangements in a body with mass only one eightieth of the earth's mass. The facts are not opposed to the conception that the moon was itself actually molten at the surface just before the satellite took on its present characteristics. In any case the total heat generated in the moon must have been enormous. By hypothesis, the total heat generated in the growing earth-knot was many multiples of 80 times greater. Can one doubt that general volcanicity in the one case would be fairly matched by complete superficial fluidity in the other?

CAUSE OF THE EARTH'S RIGIDITY

The combination of the facts known about the solar system thus interpreted by the planetesimal hypothesis furnishes a cumulative argument in favor of assuming a molten or even gaseous state for the earth's surface shell after our globe had grown to full size. Chamberlin's selection of a strongly contrasted possibility of his cosmogonic scheme is due in part to overemphasis on some elements of the scheme, especially those contrasting with essential features of the Laplacian cosmogony.

Other reasons are found in certain assumptions based on modern geophysical studies.

In the first place, he stresses the familiar principle that the melting temperatures of rock minerals are raised by pressure. Again it is a *rate,* the rate of the raising, which is absolutely vital to his argument. But it will be long before the relation of pressure and melting temperatures for the earth's core materials at their actual depths can be fixed. Meantime, one thing seems certain: pressures hundreds of times greater than those inside the earth are unable to cause the crystallization or even the liquefaction of most of the sun's substance; else the mean density would be very different from what it is. Not much weaker is the belief of astronomers concerning the non-solid nature of most of the materials in Jupiter, though these are under pressures far transcending mean or maximum pressure in the earth. Appeal to the principle here discussed has, in fact, been much overdone by many authors in their efforts to explain the earth's high rigidity.

Secondly, the proof of the earth's present high rigidity is taken by Chamberlin to mean solidity, that is, crystallinity, for the whole interior of our globe except for local "tongues" of melted rock. Even if this assumption were correct, it does not follow that the earth was similarly crystalline to the core during the period of accretion. But high rigidity does not necessarily mean crystallinity. With uniform laboratory pressures the viscosity of paraffin increases so much faster than the viscosity of nickel steel under the same pressure, that the hydrocarbon finally becomes more rigid than the steel. Rock glass, a supercooled liquid at ordinary pressure and temperature, is much more rigid than many crystalline solids. Under high, uniform pressure glass is many times more rigid than nickel steel. Under pressures of from 10,000 to 500,000 or more atmospheres, rock glass might attain, at high temperatures, degrees of rigidity quite competent to match the earth's stress-strain relations so far demonstrated. Neither seismic nor tidal vibrations within the earth demonstrate crystallinity for below the surface. If the earth's core is crystalline, the proof thereof must lie in some other direction, as yet unguessed.

For some geophysical inquiries it may be a matter of indifference whether the earth's rigidity is due to crystallinity plus pressure or to pressure alone; but Chamberlin's speculations on the shaping of the juvenile earth and on the cause of igneous action are critically affected by his choice between these alternatives.

PLANETESIMAL HYPOTHESIS IN RELATION TO IGNEOUS ACTION

The growing earth being a highly efficient furnace, by hypothesis, crystallinity could not be preserved for the interior materials, if the central heat were not quickly removed. To support his idea that liquefaction of the interior did not take place during most of the period of accretion, Chamberlin has imagined a special mechanism for the removal of heat. This involves selective mutual solution of the "more fusible" crystals and, through tidal kneading of the remaining solid materials, the upward streaming of the new magmatic "tongues" to the earth's surface. The heat is there dissipated by radiation and no longer threatens the stability of the solid state for the interior materials in general. The continuance of the crystalline state inside the earth is thus explained by the generation and rise of magmatic "tongues," and the generation and rise of the "tongues" is in turn explained by assuming a crystalline state inside the earth. The argument has some resemblance to reasoning in a circle.

RELATIVE RATES OF GENERATION AND TRANSFER OF HEAT

The rise of the magmatic "tongues" is attributed by Chamberlin to tidal kneading of the earth's body. Barrell has pointed out the comparative feebleness of the tidal stresses now affecting the earth's interior. Those affecting the small, young earth at a time when the moon's material was still largely dissipated in the planetesimal state must have been much smaller still, unless the two bodies were then closer together. However this may be, the problem of the *rate* of heat transfer by the rise of "tongues" as against the *rate* of heat generation in the earth's interior is of first importance. The planetesimal hypothesis by no means implies that the special cooling mechanism just described was more efficient than the earth-furnace during the period of accretion. If the development of heat were more rapid than the heat loss, to the point of producing general fluidity, the imagined mechanism of extrusion and differentiation of material, as well as the mechanism of cooling itself, would be destroyed.

Nevertheless, Chamberlin prefers the view that there has been a stupendous sorting of the terrestrial substances through the expulsion of "tongues" working outward in an essentially crystalline earth. He writes:

> The mutations of the inner earth may be summarized as a single prolonged process by which the more fluent, solvent, and lighter material of the earth-body was concentrated toward the surface, while the more immobile, refractory, and heavier matter was concentrated toward the

center. The result may be pictured as a central core dominated by metallic alloys and a thick enveloping sphere dominated by silicates.[8]

The core residuum is supposed to have been originally crystalline, but recrystallized, without fusion, after the manner of the familiar metamorphic rocks. During these secular changes, "the arrangement of atoms and molecules in the heart of the earth was probably controlled in the main in the interest of the internal fixation of energy and was predominantly endothermic." Chamberlin assumes, on the other hand, that energy was not stored in the radioactive elements, which have continued their break-up throughout the earth's history and at all depths. Since radioactivity is taken to be the chief source of the latent heat represented in the molten "tongues," that assumption is necessary, but it is immediately seen to rest on an unsounded mystery. The conditions for the potentialization of energy in the radioactive elements are quite unknown, but those conditions may include very high pressure and temperature, such as those prevailing deep in the earth. The laboratory tests so far made are clearly inadequate to deal with the profound mystery, the existence of which prevents confidence in the extrusive mechanism imagined and in the allied argument for permanent crystallinity of the earth's core.

DOMINANT MAGMAS

Further, differential fusibility or solubility of planetesimal materials can hardly explain the visible eruptive rocks. The dominant magmas whence these rocks have come are the basaltic and the granitic, each of nearly uniform composition from continent to continent and from ocean basin to ocean basin, and throughout geological time. They are strongly contrasted chemically. *Both* can not be the "most fusible" or "most soluble" constituents of the earth. If one is a late differentiate of the other, field evidence of the splitting might be expected; there is none.

Nor does Chamberlin's speculation explain: (*a*) the fact that the bulk of the visible granitic rocks are intrusive, while the bulk of the basaltic masses are extrusive; (*b*) the fact that the pre-Cambrian basement terranes are on the average granitic, while the eruptives of the open-ocean floors are almost entirely basaltic or derivatives of basalt. The imagined "tongues" should not have risen from the earth's interior in this selective way. On the other hand, mere inspection of the quantities involved (including the oceanic salts) forbids the notion that the granites of the continents represent a re-melted residue of secularly weathered basalt.

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[8] T. C. Chamberlin, "The Origin of the Earth," Chicago, 1916, p. 240.

Crustal Subsidence Connected with Eruption

Another fact not readily understood according to Chamberlin's mechanism of igneous action is the strong subsidence of the floors of major volcanic bodies and of laccoliths (lopoliths). The best theory of these sinkings refers them to the necessity of crustal collapse over the respective subcrustal areas whence the erupted magmas were drained. Each subsidence is readily comprehended if the feeding magmatic reservoir is a nearly or quite horizontal layer, local or general, below the crust. There is no reason to suspect that "tongues" from the deep interior would spread out at just the right depth to explain the many observed sinkings of the crust.

Eruption Largely Concentrated in Mountain Chains

Most of the post-Cambrian eruptivity of the continents is concentrated in orogenic belts, leaving the larger part of the continental surfaces free from igneous rocks. For example, the North American Cordillera has been many times, at long intervals, the scene of magmatic eruption, while the Great Plains region of Canada and the United States has witnessed little activity of that kind. Mid-continent ranges, like the Alps or Urals, and their respective environments suggest that this contrast has little to do with the meeting of continent and ocean basin. There is no apparent reason why magmatic "tongues" from the earth's core should so persistently reach or approach the surface only along the belts where the earth's surface shell is periodically wrinkled or broken. A genetic connection between orogeny and igneous activity must be assumed, but it becomes intelligible only on the supposition that the locus of eruptivity is in every case relatively close to the surface and not in the deep interior of the globe.

Eruptive Sequence

Finally, Chamberlin's speculation needs much supplementing before it can account for the general order of eruption in continental petrogenic cycles. The order is from "basic" to "acid," though often the sequence is closed by minor eruptions of "basic" magma. For reasons elsewhere detailed, this sequence seems to imply initial eruption of basaltic magma, followed, in batholithic provinces, by considerable assimilation of solid "acid" rocks, entailing differentiation of the new solutions.[9] The chief rock assimilated in batholithic chambers seems to have been pre-Cambrian gneiss of granitic composition. During post-Cambrian time the only primary magma erupted has probably been the basaltic; if so, all other pre-

Cambrian eruptives are of secondary origin. On the other hand, the older pre-Cambrian granites and gneisses, composing most of the continental plateaus, are not in similar relation to basaltic magma and must be regarded as independently erupted. If their eruption took place by the "tongue" mechanism, the composition of these melts must have been changed from the granitic to the basaltic during some part of the pre-Cambrian era, though long after the earth had reached its present size. No reason for such a systematic change is in sight if the "tongue" hypothesis of eruption be regarded as valid.

CONCLUSIONS

Many other facts of igneous geology are inexplicable on a cosmogonic theory which postulates a general solid (crystalline) condition for the earth during most of its growth. This is, however, not a necessary feature of the planetesimal hypothesis, which, apparently sound itself, points rather to the probability of a fluid state for the earth both before and for some time after accretion was completed. In a problem where so few of the essential elements can be quantitatively defined, the condition of the other planets, the satellites, and the sun is of primary importance. The planetesimal-nebula hypothesis is partly founded on the analogy of the visible spiral nebulæ. Analogy might be as fairly used to test it. However, the other planets are homologies, by hypothesis, and their testimony gives ground for deductions yet stronger than those from pure analogy. There is nothing in the dynamics of the planetesimal cosmogony which forbids belief that the earth long ago passed through a Jovian stage. To assume that its surface shell was not at least liquid when the earth attained full mass is seen to be hazardous when one reflects on the relatively slight difference between the efficiency of an earth-furnace competent to keep that shell liquid for a time and the efficiency of an earth-furnace which kept the thermal gradient and solution (fusion) curve "identical" (Chamberlin) within the globe. The identity of these two curves could persist only through a balance between heating and cooling, a balance incredibly delicate in view of the suggested origin of the planets.

Making the more probable deduction from Chamberlin's cosmogenic scheme—an earth once largely fluid from the surface downwards—the facts of geology are better understood. Among the leading facts are: (1) the density stratification of our planet, induced by early gravitative differentiation in gas or liquid; (2) the dominance of gneiss and granite in the early

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[9] R. A. Daly, "Igneous Rocks and Their Origin," New York, 1914.

pre-Cambrian complexes, which represent the rearranged material of the earth's primitive crust (a surface differentiate of low density); (3) the dominance of basalt in fissure eruptions, with other facts indicating the existence of a world-circling basaltic *couche* below the crust (the upper layer of Suess's "Sima"); (4) the genetic connection between geosynclinal downwarping and mountain-building with igneous eruption; (5) the number, lengths, and wide distribution of dikes of uniform, diabasic composition; (6) the subsidence of the floors beneath major volcanic masses and of the floors beneath the greater laccoliths; (7) certain stress-strain relations of the earth, since the high rigidity of the earth, for example, may be partly due merely to primitive differentiation according to gravity.

It may be added that the composition of the ocean ought to be quite different, if the ocean began its long life when the earth's mass had only one third or one half its present value. For, by hypothesis, the earth then had an atmosphere, rock-weathering was under way, and river salts were pouring into the ocean. Also by hypothesis, the subsequent growth of the earth was very slow. During that long accretional period, the soluble sodium must have entered the oceanic solution, most of it to remain there to this day. As a matter of fact, the sodium content of sea-water is now embarrassingly low if the earth is no older than the visible pre-Cambrian terranes!

Applied to the earth's later history, the planetesimal-nebula hypothesis thus appears to overlap the gas-nebula hypothesis. In each case a fluid state for the earth is fairly deducible from the astronomic premises. Since the objective facts of astronomy and of geology, especially igneous geology, point in the same direction, the assumption of primitive fluidity seems to be the best working hypothesis on which geology can be based. Meantime, our profound ignorance of the behavior of silicate and metallic melts at very high temperatures and pressures should prevent fixed opinion concerning the cause of the earth's high rigidity. Similarly, the mystery attaching to the original potentialization of energy in the radioactive elements makes uncertain the true relation of radioactivity to the earth's internal heat. As critical facts are slowly accumulated, the greatly appealing planetesimal hypothesis of Chamberlin and his co-workers may well serve as a foundation for geological philosophy, though the subsidiary doctrine of essential crystallinity for the earth throughout geological time be not accepted.